Laboratory Verification of a Mechanistic Subgrade Rutting Model

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The occurrence of permanent deformation or rutting is one of the major problems affecting the performance of pavement structures. In recent years, the trend toward heavier loading and higher tire pressures, as well as the substantial increase in the number of load repetitions, has significantly increased the importance of rutting phenomena.

Majidzadeh, Guirguis, and Joseph (1) have developed a rutting model based on the concept of molecular deformation as expressed by a rate process theory, and Guirguis (2) has modified the model to derive an equation of the form

$$\epsilon_p/N = A(D, W)N^{-m} \quad (1)$$

where

ϵ_p = permanent strain,
A(D, W) = intercept of the line of log (ϵ_p/N) versus log N relation with the ϵ_p/N axis,
D = deviatoric stress,
W = water content, and
m = absolute value of the slope of log ϵ_p/N versus log N straight line.

This model has been used by Montoya (3) and Buranarom (4) for the investigation of the effects of moisture and environmental change on permanent deformation. Its applicability to a wide range of clayish and silty soils and to a practical range of dynamic stresses has been studied by Khedr (5, 6).

To simplify the analysis and application of the model to engineering design, an attempt is made in this paper to relate the rutting parameters m and A to the dynamic modulus E*. This approach will simplify the problem in a manner that, given E* (either from laboratory testing or from dynamic field measurements), an estimate of the rutting potential of a given soil will be possible.

Then, if the variations of E* at various climatic conditions representing different seasons of the year that correspond to variations of moisture, density, and structure throughout the life of the pavement system are known, the rutting constants A and m can be estimated.

EXPERIMENT

In this study, both laboratory and undisturbed field samples were used for the evaluation of the model. Two basic classes of laboratory samples were used: natural silty clay and artificial water-washed, air-floated kaolin clay. Two groups of undisturbed subgrade-soil field samples were obtained from construction sites in Cuyahoga (Cleveland I-480) and Franklin (Columbus I-70) counties in Ohio. The soils at these sites are generally classified as silty clay with sand and gravel. Pertinent characteristics and properties of the tested soils are listed below.

	Soil			
Characteristic or Property	Natural Silty Clay	Artificial Kaolin Clay	Cuyahoga County (Cleveland)	Franklin County (Columbus)
Liquid limit (%)	25.3	57.6	25.3	26
Plastic limit (%)	13.0	25.2	13.0	17
Plasticity index (%)	12.3	32.4	12.3	9
Specific gravity	2.76	2.68	2.76	2.75
AASHO classification	A-4		A-2-6	A-4
FAA classification	E-5		E-5	E-6
Unified soil classification	CL	C	CL	CL

The samples were 7.06 cm (2.78 in) in diameter and 13.97 to 14.48 cm (5.50 to 5.70 in) in height. Gradation and classification tests, moisture content and dry density, and dynamic loading and unconfined compression strength tests were performed on these soil samples.

ANALYSIS OF RESULTS

The experimental data were analyzed to determine the effects of the variables considered in this investigation

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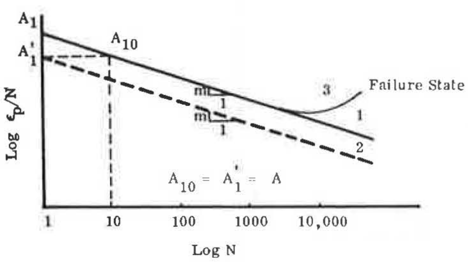
on the permanent deformation (γ_p) of laboratory-compacted and undisturbed field-subgrade samples. The parameters A and m were determined using dynamic loading test data by plotting the relation between log ϵ_p/N versus log N. According to equation 1, this plot is a straight line, m is its negative slope, and A is measured as the projected value of ϵ_p/N at N = 10.

Figure 1. Logarithmic representation of permanent deformation.



Line 1 in Figure 1 represents a typical result obtained from laboratory dynamic loading tests, while line 2 is assumed to simulate the actual contribution of the subgrade in the pavement system to the permanent deformation after construction. A_{10} is assumed to be equal to A_1' and to A. Analysis of the data has shown that such a relation is valid for a wide range of moisture contents, dry densities, dynamic stress intensities, and soil types, except for the case of very high applied dynamic stresses in which failure is occurring (curve 3, Figure 1).

Figure 2 shows typical curves of the variation of parameter m with the dynamic modulus for one of the investigated soils. E* is considered to be independent of the dry densities or moisture contents of the tested samples, i.e., E* includes the influences of moisture, density, and soil structure on the rutting parameter m. Examination of data for other soils has shown that values of m for wide ranges of dry densities, water contents, or stress intensities and for different soil types are within the narrow range of 0.82 to 0.95. In cases of exceptionally low dry density with high water content (low dynamic modulus) accompanied by a high applied dynamic stress,

Figure 2. Parameter m versus E* for natural silty clay samples.

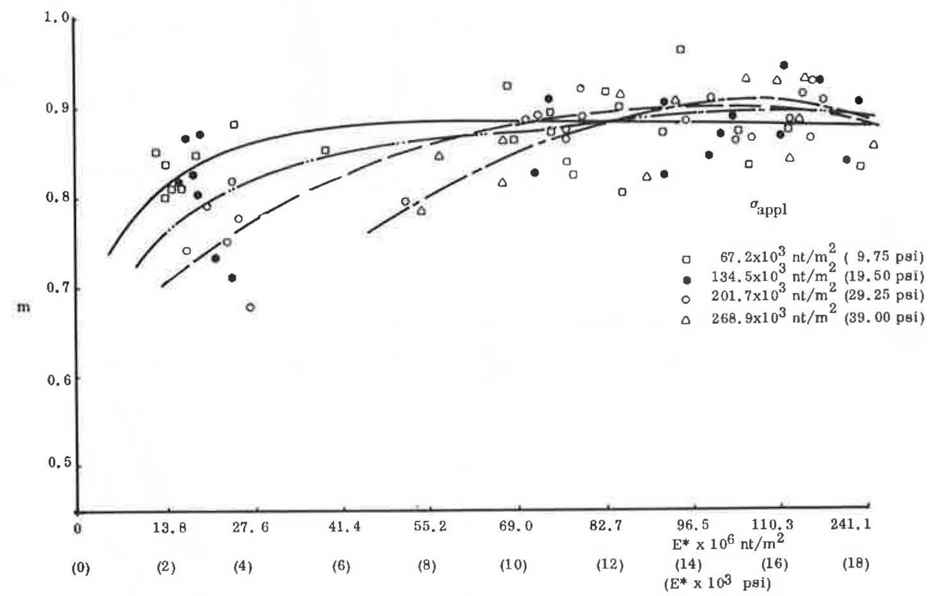
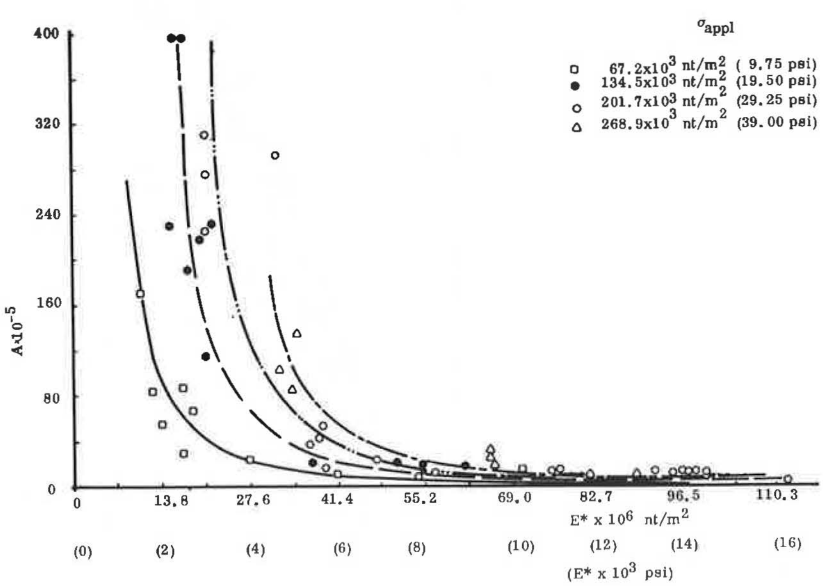


Figure 3. A versus E* at various dynamic stress intensities for artificial clay samples.



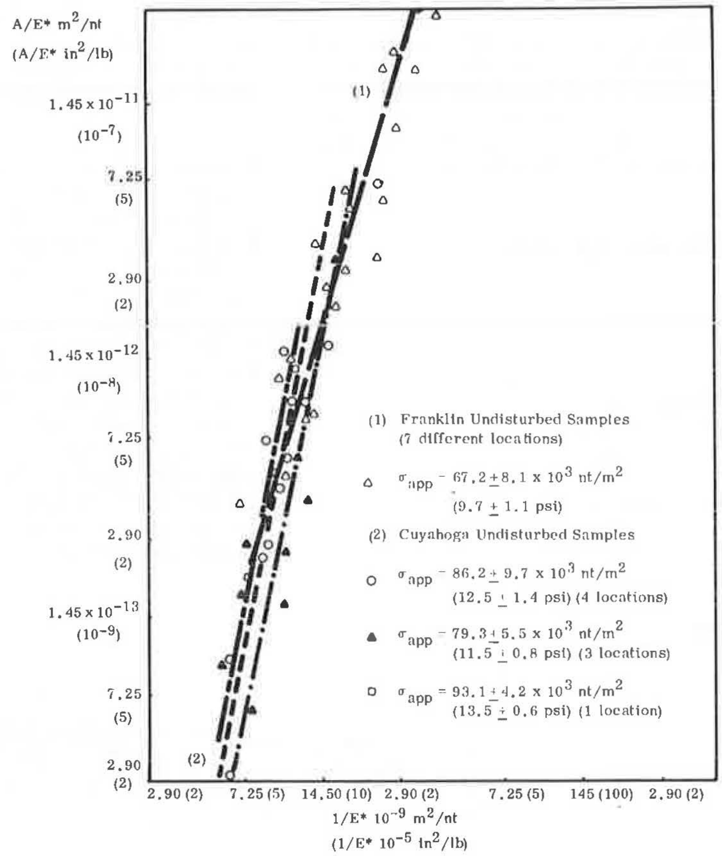


Figure 4. Log A/E* versus log 1/E* for undisturbed samples from Franklin and Cuyahoga counties.

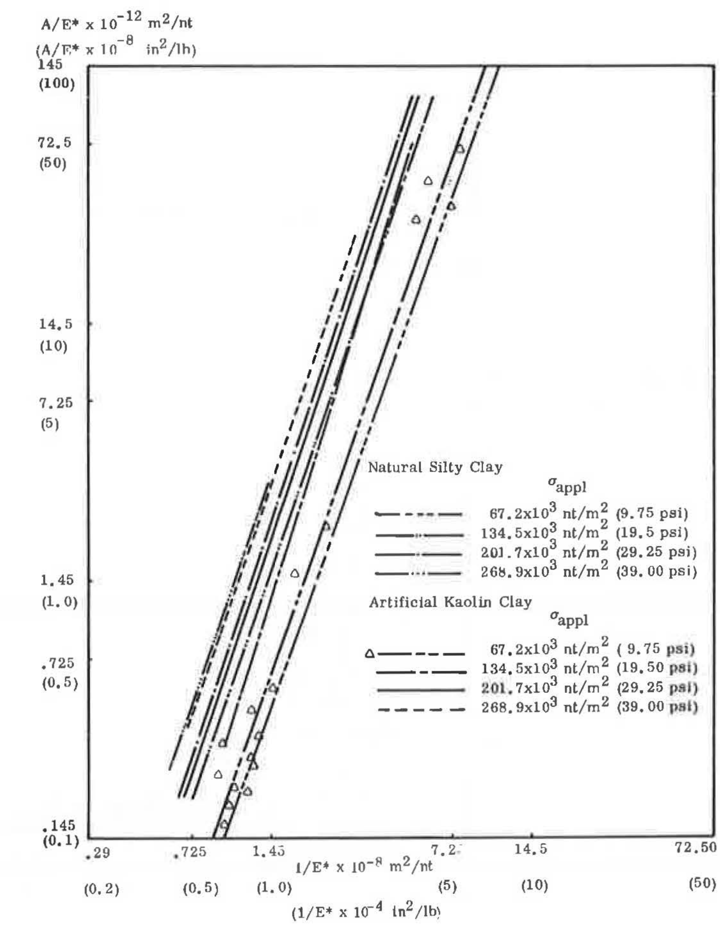


Figure 5. Relation between A/E* versus 1/E*.

m may be as low as 0.57. For soils with dynamic moduli greater than 40 MPa (6000 lb/in^2) (CBR = 4), the rutting parameter m can be represented by a constant. Comparison of the parameter m for soils such as clay, silt, or silty clay indicates that the soil type has no significant effect on the m value and therefore can be taken as a constant. Further study on other types of soils is required to examine in more detail the effects of soil type on the rutting parameter m.

The rutting parameter A is a function of the moisture content, dry density, dynamic stress, and structure of the soil. The relation between it and the dynamic modulus (E*) values is shown in Figure 3. At constant dynamic stress levels this is a power relationship. From an engineering viewpoint, the rutting parameter A can be represented in terms of two variables, E* and σ_{app}, where E* is used to characterize the soil material and account for its water content, dry density, and soil structure, and to predict the rutting phenomena.

The variations of parameters A and E* at different stress levels, moisture densities, and soil conditions are shown in Figures 4 and 5. The rutting parameter A can be described in terms of the dynamic modulus (E*) and the applied stress level.

OUTLINE OF A DESIGN SCHEME

The concepts presented in this pavement rutting model can be used to evaluate the permanent deformation of a subgrade soil with load application. The procedure to be followed is

1. Analyze the stresses in the pavement system;
2. Divide the subgrade layer into imaginary sublayers;
3. Prepare laboratory-compacted cylindrical samples or obtain undisturbed field samples;
4. Perform dynamic loading tests at the calculated or assumed stress intensities on each group of samples and calculate the parameters m, A, and E*;
5. Calculate the accumulative permanent deformation for a subgrade layer subjected to dynamic loading with seasonal environmental changes. The dynamic modulus should be measured or estimated for each seasonal change. In general, if there are (n) environmental changes and if A_{max} is the maximum value of the function A for the weakest condition of soil during these (n) changes, then at the n th environmental condition, the ϵ_p/N expression can be written as follows:

$$(\epsilon_p/N)_n = A_{max} N_n^{-m_n} \prod_{i=1}^{n-1} N_i^{(-m_i+m_{i+1})} \qquad (2)$$

where

m_i = slope of log ϵ_p/N versus log N linear relation at the i th environmental conditions,
N_i = total number of loading cycles through the i th conditions, and
N_n = total number of loading cycles through the considered (n) environmental conditions.

For $m_1 = m_2 = \ldots = m_n = m$,

$$(\epsilon_p/N)_n = A_{max} N_n^{-m} \qquad (3)$$

6. Sum the accumulative deformations of the sublayers to obtain the total contribution of the subgrade in pavement rutting, i.e.,

$$\gamma_{p_{total}} = \sum_{i=1}^{p} \epsilon_{p_i} h_i \qquad (4)$$

where

p = number of sublayers,
ϵ_{p_i} = permanent strain in the i th layer, and
h_i = thickness of the i th layer.

SUMMARY AND CONCLUSIONS

The experimental data indicate that the rutting parameters A and m are generally functions of the dynamic modulus and the applied dynamic stress. The dynamic modulus characterizes the material properties; i.e., it accounts for the water content, the dry density, and the soil structure as far as rutting criteria are concerned.

The parameter m is almost constant for normal and dense soils, but may decrease slightly for very wet soils. There is a relation between the parameter A and the dynamic modulus E*: The data show a linear relation between log A/E* and log 1/E* that is dependent on the applied dynamic stress level.

Analysis of the results obtained by Montoya (3) at different environmental conditions verifies the uniqueness of the log A/E* versus log 1/E* relation. That is, the environmental changes are reflected in the dynamic modulus E* and consequently in the values of parameter A by which permanent deformation can be evaluated.

A generalized model is presented in which the deformation for a subgrade soil layer is calculated (equations 2 and 3). The subgrade layer is divided into imaginary sublayers, the permanent strain ϵ_{pi} is computed for each, and the total contribution of the subgrade in the total pavement deformation is obtained from equation 4.

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